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Analyzing and modelling the effect of long-term fertilizer management on crop yield and soil organic carbon in China

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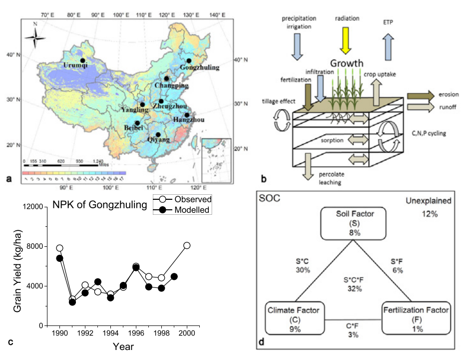
HIGHLIGHTS

- The effect of diverse fertilizer management on crop yield and SOC from simultaneous 11-year datasets of 8 long-term field experiments in China was synthesized.
- The yield and SOC under NPKM treatment were the highest while the yield under control treatment was the lowest (30%-50% of NPK yield) at all sites.
- The SOC in northern sites appeared more dynamic than that in southern sites.
- Fertilization factor contributes the most to the total variance of crop yield (42%), followed by climate and soil factor.
- The interactive influence of soil and climate determines the largest part of the SOC variance (32%).

GRAPHICAL ABSTRACT



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ABSTRACT

This study analyzes the influence of various fertilizer management practices on crop yield and soil organic carbon (SOC) based on the long-term field observations and modelling. Data covering 11 years from 8 long-term field trials were included, representing a range of typical soil, climate, and agro-ecosystems in China. The process-based model EPIC (Environmental Policy Integrated Climate model) was used to simulate the response of crop yield and SOC to various fertilization regimes. The results showed that the yield and SOC under additional manure application treatment were the highest while the yield under control treatment was the lowest (30%–50% of NPK yield) at all sites. The SOC in northern sites appeared more dynamic than that in southern sites. The variance partitioning analysis (VPA) showed more variance of crop yield could be explained by the fertilization factor (42%), including synthetic nitrogen (N), phosphorus (P), potassium (K) fertilizers, and fertilizer NPK combined with manure. The interactive influence of soil (total N, P, K, and available N, P, K) and climate factors (mean

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Long-term field experiments
EPIC model
Fertilizer management

annual temperature and precipitation) determine the largest part of the SOC variance (32%). EPIC performs well in simulating both the dynamics of crop yield (*NRMSE* = 32% and 31% for yield calibration and validation) and SOC (*NRMSE* = 13% and 19% for SOC calibration and validation) under diverse fertilization practices in China. EPIC can assist in predicting the impacts of different fertilization regimes on crop growth and soil carbon dynamics, and contribute to the optimization of fertilizer management for different areas in China.

1. Introduction

Global food demand is expected to increase rapidly in the coming decades due to population and economic growth, and food security is becoming an important issue (West et al., 2014;Godfray et al., 2010). Modern intensive agriculture relies heavily on fertilizer application, which is essential for providing crop nutrients and increasing global food production (Koning et al., 2008). Soil organic carbon (SOC) is an important factor in determining the potential productivity of agricultural soil and the arrangement of soil aggregates and their stability. Mineralization of SOC is an important source of soil nitrogen (N) and phosphorus (P). SOC content is directly affected by climate (precipitation and temperature), anthropogenic activities, and soil factors such as soil texture (Jiang et al., 2014). In addition, soil and crop management, including crop residue management and fertilization practices, especially the use of mineral fertilizers, and manure amendments, have a large influence on soil fertility and thus crop yields (Zhang et al., 2010). Therefore, assessing the effect of long-term fertilization on crop yields and SOC content is currently an important issue for soil fertility, crop production, and food security.

In China, a national network of long-term fertilizer experiments has been established since the early 1980s across highly diverse soil types, climatic zones and management practices (National Soil Fertility and Fertilizer Effects Long-term Monitoring Network) (Zhao et al., 2010). Numerous datasets of soil physical and chemical properties, nutrient content, climate records and agricultural management have been collected annually, which enable researchers to explore the relationship between fertilization and multiple factors across a wide range of spatio-temporal scales. However, previous studies in China focused on the changes in crop yields or SOC content based on a few experimental sites (Zhang et al., 2008), while long-term comparative studies on a large scale are lacking. Also, studies in China that combine long-term field experiments and model simulations of both crop yield and SOC content, enabling extrapolation to other regions, are not available.

Process-based models are useful tools for describing and predicting the consequences of long-term fertilizer management. The Environmental Policy Integrated Climate model (EPIC, Williams et al., 1989) is a field-scale, process-based model that can simulate plant growth and crop yield, soil erosion, soil nutrient cycling and the effects of crop management on plants, water, and soil (Gaiser et al., 2010). It has been successfully employed worldwide to study crop yield and yield gaps (Schierhorn et al., 2014;Lu and Fan, 2013), climate change impacts on crop yield (Niu et al., 2009;Xiong et al., 2016), environmental impacts (Liu et al., 2010;Liu et al., 2016b), soil erosion and nutrient leaching (Bouraoui and Grizzetti, 2008), and crop management operations (Thomson et al., 2006). However, it has rarely been validated against

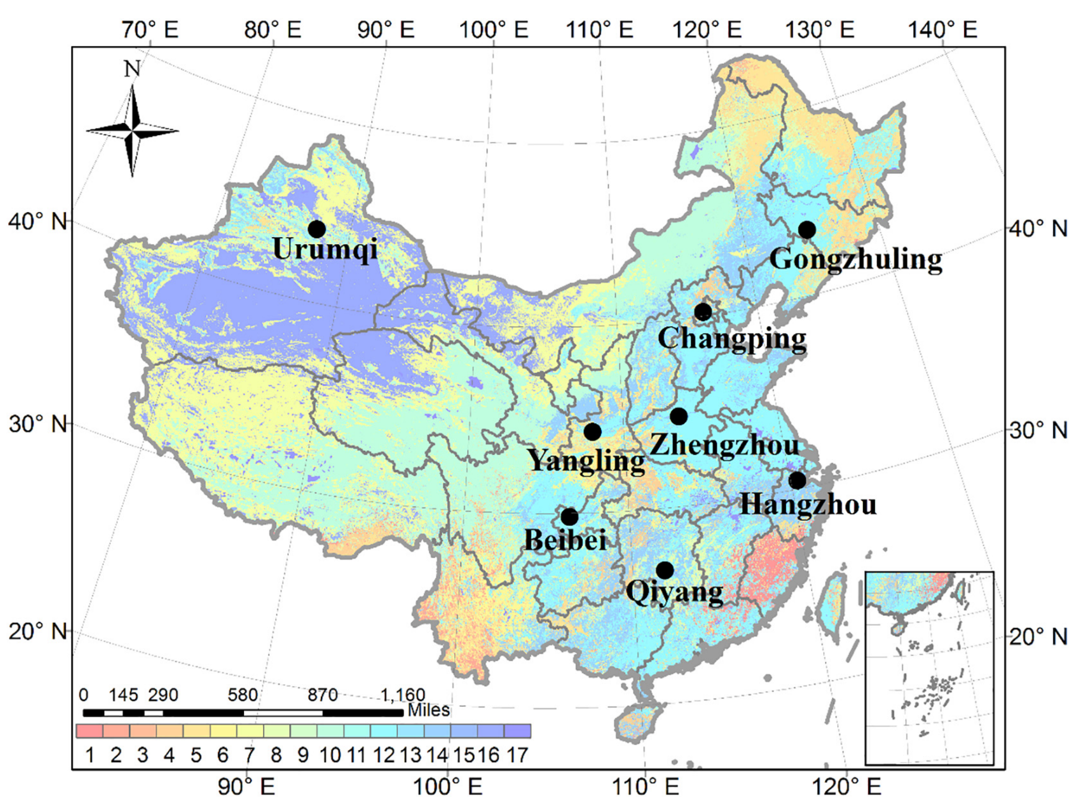

Fig. 1. The eight experimental sites of the National Soil Fertility and Fertilizer Effects Long-term Monitoring Network, including Gongzhuling (GZL) in Jilin Province, Changping (CP) in the Beijing City area, Urumqi (Urum) in Xinjiang Province, Yangling (YL) in Shaanxi Providence, Zhengzhou (ZZ) in Henan Province, Hangzhou (HZ) in Zhejiang Province, Beibei (BB) in the Chongqing City area, and Qiyang (QY) in Hunan Province. The background map is the 1 km resolution MODIS land cover data with the IGBP classification scheme.

Table 1
Location, climate, crop rotation, and crop species of the 8 long-term fertilization experimental sites in China.

Name[a]	Location	Climate[b]	Mean annual precipitation (mm)	Mean annual temperature (°C)	Crop rotation[c]	Crop species
GZL	43.51°N, 124.81°E	MT-SH	550	5	M	Danyu 13,Jidan 222,Jidan 209
CP	40.21°N, 116.2°E	WT-SH	529.7	13	WM	Tangkang 5(M); 8693(WW)
Urum	43.94°N, 87.47°E	MT-SA	241.7	7.6	MWW	SC-0704(M); Xinchun 2(SW); Xindong 17(WW)
YL	34.3°N, 108.01°E	WT-SA	525	13.8	WM	Shandan 9,Shan 902(M);Xiaoyan 6, Shan 229, Shan 253(WW)
ZZ	34.78°N, 113.66°E	WT-SH	645.6	14.8	WM	Zhengdan 8(M); Linfen 7203, Zhengzhou 941, Yumai 47 (WW)
HZ	30.43°N, 120.42°E	SN-ST	1550	16	BRR[d]	Zhenong 3(B) Fuxuan 6(ER) Yuanjing 4(LR)
BB	29.81°N, 106.41°E	SN-ST	1544.8	18.3	WR[d]	Shanyou 63,Eryou 6078(R); Xinongmai 1(W)
QY	26.75°N, 111.88°E	SN-ST	1407.5	18.1	WM[d]	Yedan 13(M) Xiangmai 1(WW)

[a] Locations are indicated in Fig. 1. GZL: Gongzhuling in Jilin province; CP: Changping in Beijing city; Urum: Urumqi in Xinjiang province; YL: Yangling in Shaanxi province; ZZ: Zhengzhou in Henan province; HZ: Hangzhou in Zhejiang province; BB: Beibei in Chongqing city; QY: Qiyang in Hunan province.
[b] MT = mild temperate; SH = semi-humid; SA = semi-arid; A = arid; WT = warm temperate; SN = subnormal; ST = subtropical.
[c] M: single-cropping, maize; WM: double-cropping, winter wheat/maize annually; MWW: triple cropping, maize/spring wheat/winter wheat annually; BRR: triple cropping, barley/early rice/late rice annually; WR: double-cropping, winter wheat/rice annually.
[d] Rice transplanting is the dominant practice in Hangzhou (HZ) and Beibei (BB). Intercropping is dominant in Qiyang (QY).

long-term experimental field data to study the influence of various long-term fertilization on crop yield and SOC dynamics across broad environmental conditions and in wide spatiotemporal scales.

This study focuses on the effects of different fertilization regimes on crop yield and SOC content by analyzing data from long-term field trials in China, using the EPIC model, and the variance partitioning analysis (VPA) approach. The data includes eight long-term field experiments with four fertilizer treatments collected across China (from 1990 to 2000), covering all experimental sites in the China National Soil Fertility and Fertilizer Effects Long-term Monitoring Network comprising a wide range of climate and soil conditions. We quantify how different soil and climate factors, and fertilization practices affect the variations in crop yield and SOC.

2. Materials and methods

2.1. Long-term experimental data

The China National Soil Fertility and Fertilizer Effects Long-term Monitoring Network was established in 1989 in nine typical agricultural areas (site Guangzhou no longer exists due to urbanization so only eight were left) to investigate the effects of long-term inorganic and organic fertilizers on crop yield, soil fertility and environmental impacts all over China. In our study, the data from eight long-term experimental sites were obtained, with consistent information on soil types, climate conditions, cropping systems and field management practices in distinct climatic zones (Fig. 1 and Table 1), namely Gongzhuling (GZL), Changping (CP), Urumqi (Urum), Yangling (YL), Zhengzhou (ZZ), Hangzhou (HZ), Beibei (BB) and Qiyang (QY). These long-term experiments with consistent fertilizer and manure comparative trials represent the most important agro-ecosystems, crop species, and agricultural practices in China (Tang et al., 2008).

The fertilizer and manure treatments in this study include (1) control with no fertilizer or manure application (CK), (2) chemical N, P and potassium (K) fertilizers (NPK), (3) chemical N and K (NK), and (4) NPK with animal manure (NPKM). Data on location, climate, crop rotation, and crop species for each site are listed in Table 1. The types and application rates of N, P, K chemical fertilizer and manure are listed in Table 2.

Other agricultural management practices also vary across sites. Soil tillage is conducted once or twice a year (YL, once before wheat planting; GZL and QY, once shortly after crop harvest) (Liang et al., 2016). The depth of tillage is 15–20 cm in all sites, except for ZZ where the soil is tilled to a depth of 30 cm. Irrigation is by flooding, while the amount of irrigation water differs by site and crop. Rice is transplanted in site HZ and BB, which is a common technique in China, whereby seedlings are raised in nursery beds and transplanted to the field after 1 to 2 months. A wheat-maize intercropping system is used in QY. Winter wheat is planted between 5th and 11th of November and harvested

Table 2
The types and application rates of chemical fertilizer and manure of the long-term fertilization experiments at the eight experimental sites[a].

Site	N fertilizer		P fertilizer		K fertilizer		Manure				
	Type	N (kg/ha)	Type	P (kg/ha)	Type	K (kg/ha)	Type	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	C (g./kg)
GZL	Urea	165(maize)	Superphosphate	36.02	K_2SO_4	68.48	Pig manure	5.0	1.8	4.1	106
CP	Urea	150(winter wheat) 150(maize)	Superphosphate	32.75	KCl	37.35	Pig manure	8.0	1.0	2.5	189
Urum	Urea	241(maize) 241(spring wheat)	Superphosphate	32.75	K_2SO_4	37.35	Sheep manure	3.1	1.1	2.7	60
YL	Urea	165(winter wheat) 187.5(maize)	Superphosphate	60.25	K_2SO_4	48.14	Cattle manure	11.5	5.7	9.0	201
ZZ	Urea	99 + 66(winter wheat) 112.5 + 75(maize)	Superphosphate	60.25	K_2SO_4	48.14	Horse manure	11.5	5.7	9.0	201
HZ	Urea	75(barley) 150(early rice) 150(late rice)	Superphosphate	57.63	KCl	68.48	Pig manure	5.5	2.5	2.9	138
BB	Urea	90 + 60(wheat) 90 + 60(rice)	Superphosphate	65.49	K_2SO_4	77.85	Farmyard manure	2.0	0.7	1.8	43
QY	Urea	90(winter wheat) 210(rice)	Superphosphate	36.02	KCl	68.48	Pig manure	5.5	2.5	2.9	138

[a] For the location and names of sites see Fig. 1 and Table 1.

Table 3
Crop sequence[a] recorded at the eight experimental sites during the period 1990–2000.

Site[b]	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1. GZL	M	M	M	M	M	M	M	M	M	M	M
2. CP		WM	WM	WM	WM	WM	WM	WM	WM	WM	WM
3. Urum	M	SW	WW	M	SW	WW	M	SW	WW	M	M
4. YL		WM	WM	WM	WM	W		WM	WM	WM	WM
5. ZZ		WM	WM	WM	WM	WM	WM	WM	WM	WM	WM
6. HZ (Transplanting)		BRR	BRR	BRR	BRR	BRR	BRR	BRR	BRR	BRR	BRR
7. BB (Transplanting)			WR	WR	WR	WR	WR	WR	WR	WR	WR
8. QY (Interplanting)		WM	WM	WM	WM	WM	WM	WM	WM	WM	WM

[a] M: single-cropping, maize; WM: double-cropping, winter wheat/maize annually; SW: spring wheat; WW: winter wheat; BRR: triple cropping, barley/early rice/late rice annually; WR: double-cropping, winter wheat/rice annually. Missing data were inserted by extending the sequence from previous and following years.
[b] For the location and names of sites see Fig. 1 and Table 1.

between 11th and 22nd of May, and maize is planted on 7th April and harvested on 20th of July (one month of overlap). Details on the crop rotations are provided in Table 3.

Soil samples are randomly taken from the topsoil (0–20 cm depth) from each plot in each site after harvest but before tillage (e.g. September–October). Five to ten core samples with 5 cm diameter are taken in each plot and mixed thoroughly, air-dried and sieved (<2 mm) for soil pH analysis (1:1 *v*/v water) and further ground (<0.25 mm) for other physiochemical analysis. Classical analytical methods are used to measure SOC (Walkley and Black, 1934), total nutrient (N, P, K) concentrations (Black et al., 1965;Murphy and Riley, 1962; Knudsen et al., 1982), available N and K (Lu, 2000) and available P (Olsen, 1954). The particle-size distribution and bulk density are also measured every year by classical analytical methods. Soil types at each site are classified based on United Nations Food Agriculture Organization (FAO) soil taxonomy system (FAO-Unesco, 1974).

2.2. Description of EPIC

2.2.1. General

EPIC is a process-based agro-ecosystem model providing tools for simulating crop growth and SOC dynamics with a daily time step. It includes modules representing crop growth, weather, soil hydrology, soil temperature, nutrient and C cycling as well as crop management practices, including tillage, fertilization, and irrigation (Fig. 2). It was developed by the USDA to assess the influence of agricultural activities on US soil and water resources (Sharpley and Williams, 1990) and has been continuously improved into the present comprehensive agro-ecosystem model. Here we use the version EPIC0810.

2.2.2. Crop yield simulation

The EPIC model uses one crop growth routine and a unified approach to simulate a wide range of crops, which facilitates a consistent calibration procedure (Xiong et al., 2014). In the crop growth routine, potential daily crop growth is calculated based on the interception of photosynthetically active solar radiation, radiation-use efficiency and multiple crop parameters, such as leaf area index. The potential daily increase in biomass estimated by the approach presented by Monteith and Moss (1977) is corrected for water stress, N and P availability, temperature, soil aeration, and salinity and aluminum stresses to arrive at actual daily yield. At maturity, crop dry-matter yield is calculated from the above-ground biomass and the crop specific harvest index (Williams et al., 1989). Fresh matter is calculated by using a moisture content of 14% (Bessembinder et al., 2005).

2.2.3. SOC simulation

EPIC provides a comprehensive module to simulate dynamics of soil organic C and N, interacting with soil moisture, temperature, tillage, soil density, erosion, and leaching (Izaurralde et al., 2006). Carbon from aboveground crop residues, root material, and organic amendments is added to the soil surface or belowground, and transformed into soil organic C and N compartments based on lignin and N contents. Soil organic C and N are allocated to three pools as in the Century model (Parton et al., 1983), i.e. microbial biomass, slow humus, and passive humus with different turnover times (days or weeks for microbial biomass to hundreds of years for passive organic matter) (Izaurralde et al., 2006).

2.3. Input data

Weather data required by EPIC was obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do) from1990 to 2000. For each site, daily solar radiation (MJ m^{-2}), maximum and minimum air temperature (°C) and precipitation (mm) were collected from the nearest meteorological station. Potential heat units (PHU) required by crops to reach maturity were calculated based on the planting and harvest dates and the weather data during the growing period.

When the long-term field trials started, the soil profile was described at each site and soil samples were taken from each horizon. The number of horizons varied from 3 to 7 depending on the site. Basic physical soil properties, including horizon thickness, topsoil clay content, bulk density, soil water content at field capacity, saturated hydraulic conductivity, and soil texture were measured, as well as basic chemical soil properties for all soil horizons, including initial soil organic matter content, total N, P and K content, alkali-hydrolyzable N, available P and K, pH, and cation exchange capacity (CEC). The initial soil profile data (Table 4) was used as inputs for EPIC. Besides, topsoil samples (0–20 cm depth) were collected to analyze SOC, plant nutrients (total N, P, K, alkali-hydrolyze N, and available P and K), pH, and soil physical

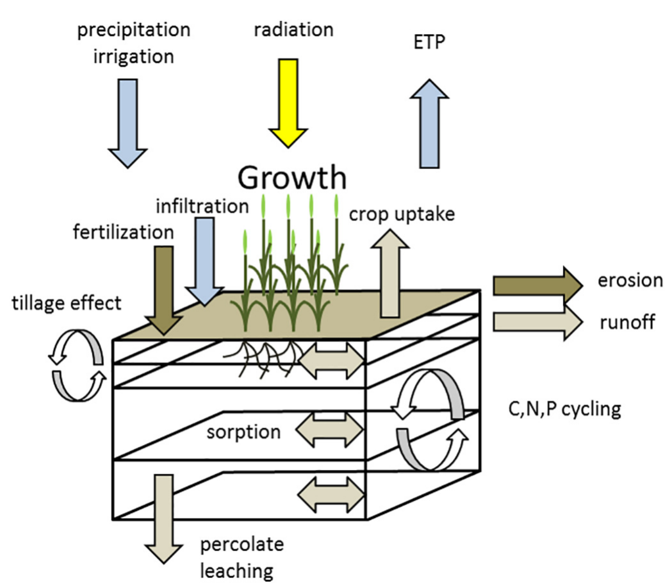

Fig. 2. Schematic representation of the EPIC model (based on Williams et al. (1989)).

Table 4
Initial soil physical and chemical properties for the topsoil (0-20 cm) at the 8 experimental sites during the first survey.

Site[a]	Soil classification in FAO	pH	Clay (%)	Bulk density (g cm^{-3})	Soil porosity (%)	Soil organic matter (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})
GZL	Luvic phaeozems	7.6	31.1	1.19	53.39	22.8	1.34	0.546
CP	Haplic luvisol	8.6	50	1.58	40.37	11.37	0.649	0.694
Urum	Haplic calcisol	7.9	87	1.1	54.3	17.4	1.03	0.361
YL	Calcaric regosol	8.9	51.6	1.35	49.62	10.8	0.897	0.637
ZZ	Calcaric cambisol	8.3	10	1.55	42.1	11.26	0.699	0.733
HZ	Hydragric anthrosol	6.0	20	0.67	nd[b]	27.4	0.419	0.31
BB	Calcaric regosols	8.7	34	1.21	nd[b]	16.57	0.757	0.546
QY	Eutric cambisol	5.7	61.4	1.27	52.1	15.88	1.07	0.52

[a] For the location and names of sites see Fig. 1 and Table 1.
[b] nd = no data.

properties (field capacity, soil porosity, and bulk density) every year after harvest, but before tillage (Ma et al., 2009;Zhang et al., 2010).

Annual grain yield and shoot biomass were also recorded, as well as management practices including tillage, fertilization, sowing, irrigation, and harvesting. According to the standard management plan from 1989, the same management practices (with only minor changes according to the local weather) were performed every year, so the time series represent the long-term effects of every single variable. Based on the experimental management records, the corresponding crop operation schedules were designed in EPIC for each treatment and site, including sowing and planting, tillage, fertilizing, irrigation and harvesting operations.

2.4. Model calibration, validation, and evaluation

2.4.1. Model calibration and validation

Model simulations were set-up based on the historical crop rotations and farm practices' investigation from the monitoring sites. For each site, crop yield and SOC of individual treatments for the period 1990–1996 and 1997–2000 were used to calibrate and validate the model, respectively. The eight monitoring sites represent different cropping systems including different species (maize, winter wheat, spring wheat, barley, early rice and late rice) and crop rotation. Minor adjustments to the default crop parameters provided by EPIC developers were made to describe local crop cultivars more appropriately (Table 5). The optimal temperature for crop growth, harvest index (HI), maximum crop height and PHU were modified according to local crop species information. The PHU values were estimated by fitting the heat unit index (HUI) to reach ~100%, assuming that crops were harvested at maturity, and taking a post-maturity drying on the field into account. HUI is defined as a fraction of PHU when operations occur during the growing season, and it ranges from 0 at sowing or planting to 100% at maturity (Wang et al., 2012). For crop varieties, such as early rice, late rice and barley in Southern China, the HI and the energy conversion ratio (WA) were adjusted (Table 5). We used the Hargreaves method to calculate potential evapotranspiration, with small adjustments to its default parameterization in order to match the observations in different climatic regions (Liu et al., 2016a). The original parameterization of organic C and N routine as proposed by Izaurralde et al. (2006) was used, with small parameter adjustments. The adjustments were summarized in Table 5.

2.4.2. Model statistical evaluation

The agreement between modeled and measured data was evaluated by the normalized root mean square error (*NRMSE*), which represents the (normalized) relative size of the average difference between observations and model (Eq. 1) (Willmott, 1982). The *NRMSE* values ≤50% indicate acceptable model performance (Beusen et al., 2015).

$$NRMSE = \frac{100}{\overline{M}}\sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \quad (1)$$

Where S_i and M_i are simulated and measured values in the i-th realization, respectively. n is the number of values and $\overline{M}$ is the average value of measurements.

2.4.3. Variance partitioning analysis

The variance partitioning analysis (VPA) is a common method in ecology used to determine how independent factors explain the variance in a dependent variable. In this study, we used VPA to study the contribution of soil (S), climatic (C), and fertilization (F) factors and their interactions to crop yield and SOC variance. Soil factors considered are total nitrogen, phosphorus, potassium (TN, TP and TK respectively, all in g kg^{-1} soil), available N, P, K (AN, AP and AK respectively, in g kg^{-1} soil), pH and soil bulk density (BD in g cm^{-3}) from 1990 to 2000 for all treatments (NPK, CK, NK and NPKM) and all eight sites. Climate factors include mean annual temperature (MAT, in °C) and mean annual precipitation (MAP, in cm) from 1990 to 2000 for each treatment and

Table 5
Key parameters of EPIC to simulate crop yield and SOC.

Parameter	Description	Range	1	2	3	4	5	6	7	8
PSP	Phosphorus sorption ratio	0.05–0.75	0.15	0.1	0.1	0.1	0.1	0.1	0.2	0.5
PARM (20)	Microbial decay rate coefficient	0.1–1.5	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
PARM (77)	Coefficient regulating p flux between labile and active pool	0.01–0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
PARM (13)	Hargreaves PET equation coefficient	0.0023–0.0032	0.0023	0.0032	0.0021	0.0023	0.0023	0.0021	0.0022	0.0032
HI[a]	Harvest Index. The ratio of grain yield to the total biomass	0–1	M:0.5	M:0.5; WW 0.45	WW:0.45	M: 0.5; WW: 0.45	B,R: 0.45	WW: 0.45; R:0.5	WW: 0.45; R: 0.5	WW:0.45; M:0.5
TOPC[a]	Optimal temperature for plant growth (°C)		M:25	M:25; WW:15	M:22.5; SW:20; WW:15	M:25; WW:25	M:25; WW:15	B:15;R:25	WW:15; R:25	M:25; WW:15
HMX[a]	Maximum crop height (m)		M:2.8	M:2; WW:0.679	M:2;SW:0.9; WW:1.1	M:2.45	M:2; WW:0.825	B:0.905; R:1.06	WW:0.86; R:1.06	M:2.25; WW:0.85;

[a] M: maize; SW: spring wheat; WW: winter wheat; R: rice; ER: Early rice; LR: Late rice; B: barley.

site. Fertilization factors are fertilizer N, P and K (in kg/ha) together with manure N and P (MN and MP) inputs from 1990 to 2000 for each treatment and site. The soil, climatic and fertilization factors are the independent factors, while crop yield together with SOC is the dependent factors in this analysis. All statistical analyses were carried out using R version 3.2.2 (R Core Team, 2014). The VPA analysis was calculated using the Vegan package in R (Legendre and Legendre, 2012). The significant level is set at $P < 0.05$ throughout the study.

3. Results

3.1. Effect of long-term fertilization on crop yield

For both single- and double-cropping systems, the annual crop yields in plots with fertilizer application exceed those in the treatments without fertilizers. Among all sites, the lowest average annual yields are measured in control plots (CK, 3.0 t ha^{-1} for maize, 1.3 t ha^{-1} for wheat,

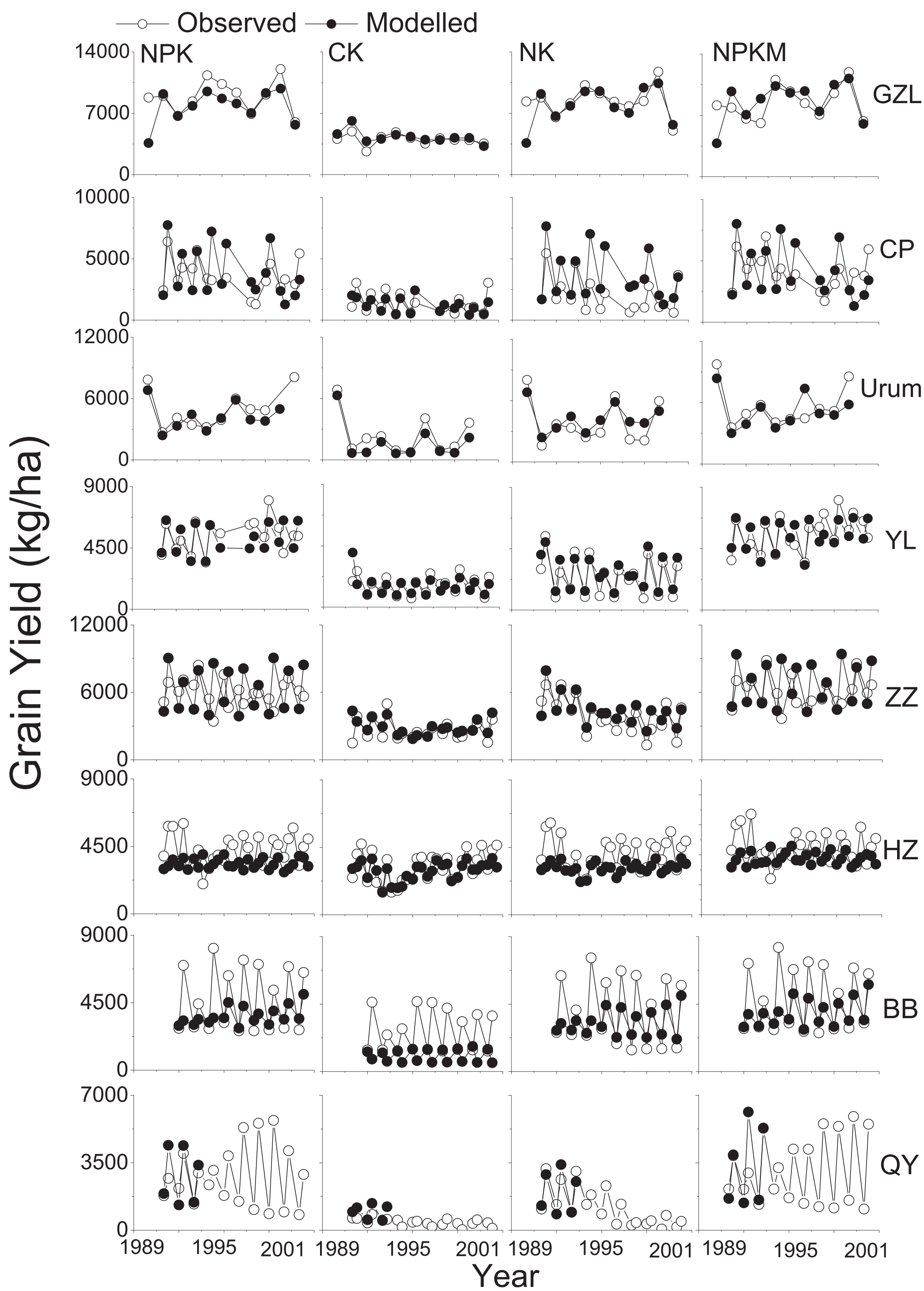

Fig. 3. Observed and simulated crop yield for the eight experimental sites (see Fig. 1 and Table 1) for the period 1990 to 2000. Sites may have mono- (e.g. GZL), double (e.g. YL) or triple cropping (Urum). Each dot represents one crop.

2.39 t ha^{-1} for barley and 3.7 t ha^{-1} for rice), while the highest yields are observed under NPKM treatments (6.6 t ha^{-1} for maize, 4.3 t ha^{-1} for wheat, 3.9 t ha^{-1} for barley and 5.4 t ha^{-1} for rice) (Fig. 3). The annual average crop yield under NPK is the second highest, with 6.4 t ha^{-1} for maize, 4.2 t ha^{-1} for wheat, 3.4 t ha^{-1} for barley and 5.2 t ha^{-1} for rice, while the yield under the NK treatment is 5.2 t ha^{-1} for maize, 2.0 t ha^{-1} for wheat, 3.2 t ha^{-1} for barley and 4.9 t ha^{-1} for rice (Fig. 3). P fertilizer can help to improve the crop yield at all sites and wheat is more sensitive to P fertilizer application among all the crops.

There is large inter-annual variability under the same treatment, which is mainly caused by precipitation during the growing season (Fig. 4). For some sites, yield and precipitation are not correlated, mainly due to irrigation (e.g. site Urum). For the same crop, there is also a large spatial heterogeneity among different sites. For example, the yield of maize in GZL (annual average of 8.9 t ha^{-1} for NPK, 4.0 t ha^{-1} for CK, 8.4 t ha^{-1} for NK and 8.4 t ha^{-1} for NPKM) is significantly higher than in other sites, while QY (annual average of 4.0 t ha^{-1} for NPK, 0.4 t ha^{-1} for CK, 1.7 t ha^{-1} for NK and 4.6 t ha^{-1} for NPKM) has the lowest yield due to the low soil pH (Table 1; Fig. 3).

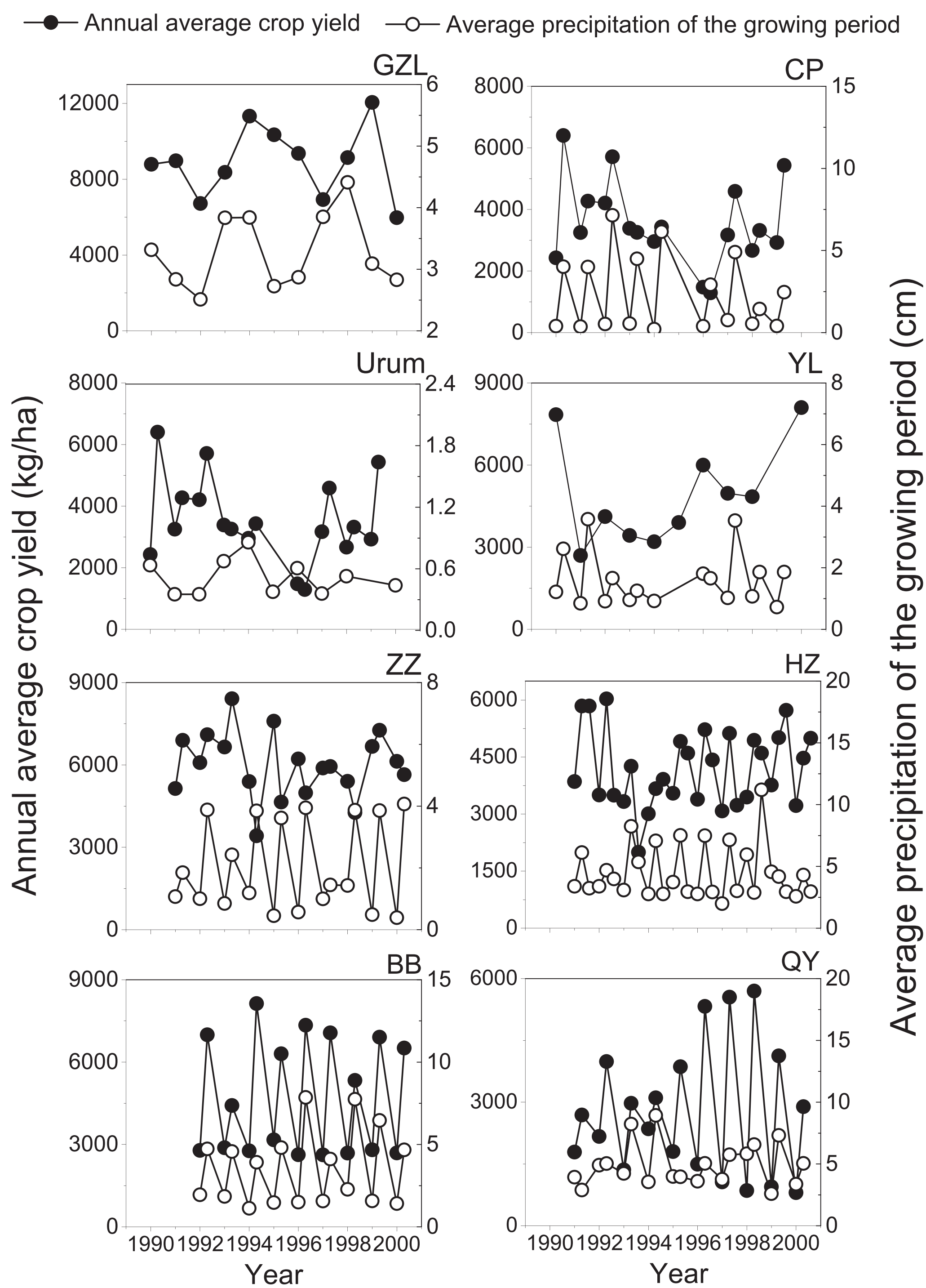

Fig. 4. Annual crop yield (left) and average precipitation during the growing period (right) for the NPK treatment for the 8 experimental sites during the period 1990 to 2000.

3.2. Effect of long-term fertilization on SOC

Manure application leads to significant increases of SOC. The average the SOC content from 1990 to 2000 for all sites under four treatments under NPKM is 31 t C ha^{-1}, 27 t C ha^{-1} for NPK, 26 t C ha^{-1} for NK, and 25 t C ha^{-1} for CK (Fig. 5). The SOC content under manure treatment is the highest, and the plots with inorganic fertilizers have higher SOC than the control plots. In addition, SOC under NPKM treatment demonstrates the largest increase (27 to 36 t C ha^{-1} from 1990 to 2000). Under NPK treatment, SOC increases from 26 t C ha^{-1} in 1990 to 30 t C ha^{-1} in 2000, while the SOC increase under NK is small (increase from 27 t C ha^{-1} to 29 t C ha^{-1} during 1990–2000). SOC

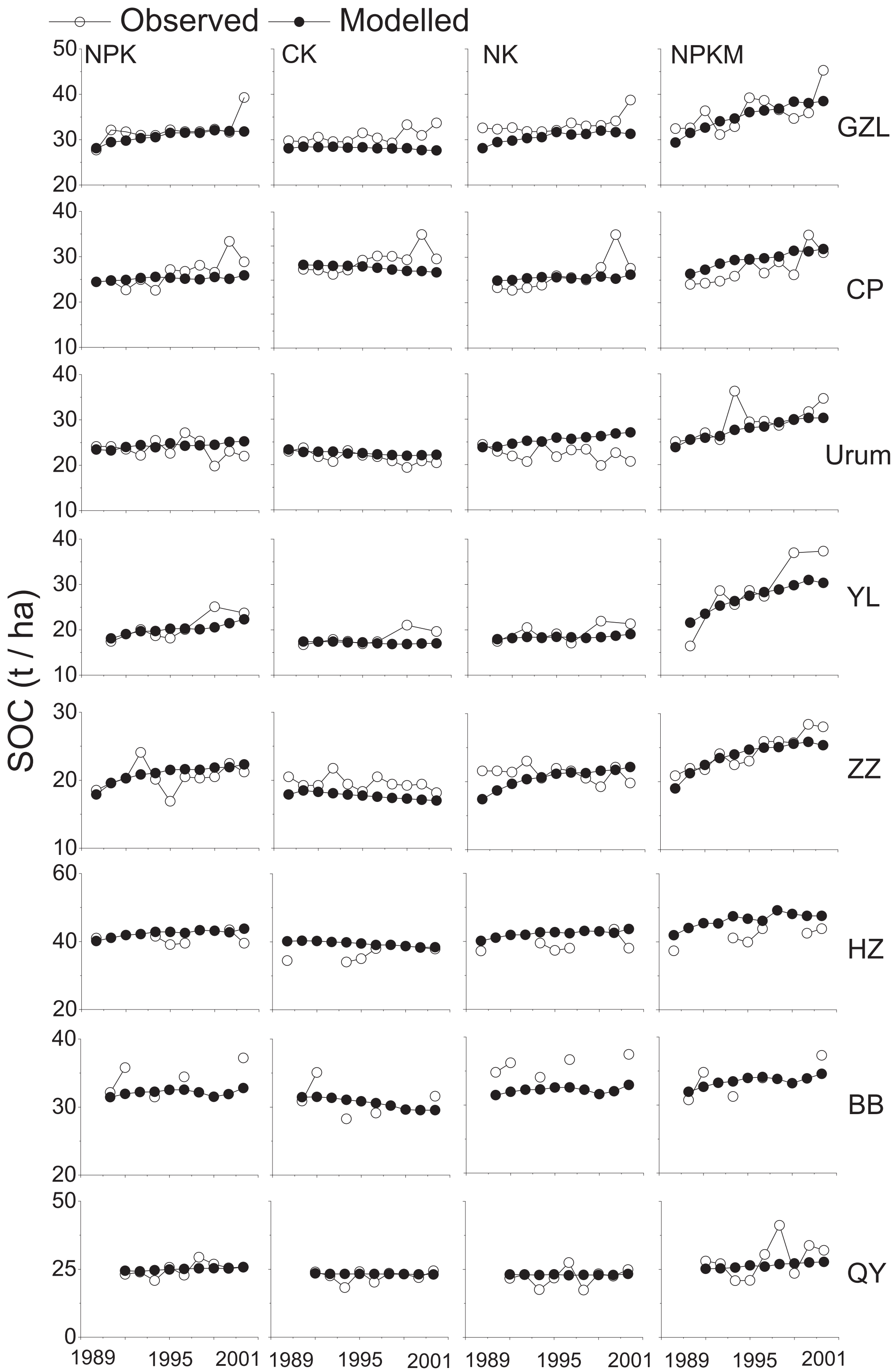

Fig. 5. Observed and simulated SOC for the 8 experimental sites (see Fig. 1 and Table 1) for the period 1990 to 2000. Sites may have mono- (e.g. GZL), double (e.g. YL) or triple cropping (e.g. *Urum*). Each dot represents one crop.

remains relatively stable under CK (increase from 25 to 26 t C ha^{-1}). The SOC in northern sites (GZL, CP, Urum, YL, and ZZ) appeared more variable than that in the southern sites (HZ, BB, and QY). SOC increases under all fertilization treatments during the entire period at GZL, CP, YL, and BB, while it decreases at Urum under NPK, CK, and NK treatments. SOC in QY is relatively stable under NPK, CK and NK. The values of SOC observed in HZ and ZZ demonstrate large variation among different treatments.

3.3. Modelling crop yield and SOC

EPIC adequately simulates crop yields under all treatments. The modeled and measured crop yields show a good agreement with *NRMSE* equals 32% and 31% for calibration and validation subsets, respectively (Figs. 3 and 6). A detailed statistical evaluation shows that the modeled crop yields agree satisfactorily with the observations for all treatments and sites (Figs. 3 and 6). For QY, soil pH was 5.7 in 1990 and it decreased significantly in the following years. After 11 years, the pH values under NPK, CK, and NK are 4.7, 5.6 and 4.7, respectively (Cai et al., 2011). The decline of soil pH leads to the overall yield decline of wheat and maize (Cai et al., 2011).

The EPIC model properly simulates the SOC dynamics in all treatments (Figs. 5 and 7). For all sites, the *NRMSE* between measured and modeled SOC is 13% for the calibration subset, and 19% in the validation subset. The modeled SOC values demonstrate lower variation compared to the observed values (Fig. 5). Both modeled and measured SOC show a slight increase in plots with organic and inorganic fertilizer and a declining trend in most plots under the CK treatment.

3.4. The proportional contributions to crop yield and SOC variations

Among all fertilization treatments and experimental sites, 80% of the total variability in crop yield can be explained by soil, climate and fertilization factors and their interactions ($P < 0.05$). The three individual factors alone explain 10%, 10%, and 42% respectively (Fig. 8a). The fertilization factor has the largest contribution (42%). The interactions between soil, climate and fertilization factors explain 2%, 5%, and 2% of the crop yield variability. The overall interactive contribution of all three factors together is 9% (Fig. 8a).

Almost 89% of the total variance in SOC can be explained by soil, climate and fertilization factors and their interactions (Fig. 8b). In contrast to the significant contribution of fertilization to the crop yield variance, the SOC variability caused by fertilization alone (1%) is substantially smaller than that explained by the soil (8%) and climate factors (9%). The overall interactive influence of the three factors together shows the largest contribution to the variance in SOC (32%), followed by the interactive contribution between soil and climate factors (30%). The total variance explained by the interactions between soil and fertilization factors is 6% (Fig. 8b).

4. Discussion

4.1. Influence of fertilization on crop yield and SOC

Application of mineral fertilizers and manure can lead to increasing SOC and crop yield. Our results show that the yield and SOC under NPKM management are the highest, followed by NPK, NK, and CK. Soil carbon sequestration is a homeostasis process related with SOC decomposition and carbon input from crop roots, straw, and manure. Manure application leads to significant enhancement of SOC, which confirms other field experiments and studies (Zhang et al., 2015;Jiang et al., 2014;Hua et al., 2016;Zhang et al., 2016b). The massive C inputs from manure can contribute greatly to SOC. Furthermore, manure application is an important source of soil N and P which can reduce the N and P constrains on crop growth and SOC build-up (Stewart et al., 2009;Zhang et al., 2009). During the past decades inorganic fertilizers have been used to enhance crop yields in China. While crop yields increased largely over this period, SOC stocks changed slightly. There is no obvious increase in SOC under CK and NK treatments, which is consistent with other research (Goyal et al., 1992;Su et al., 2006;Liu et al., 2013;Zhang et al., 2010). Under non-fertilization and unbalanced fertilization, the soil nutrient availability is generally low and limiting to crop growth, leading to low productivity and carbon input from roots (Su et al., 2006;Jagadamma et al., 2008). SOC may even decrease when carbon input is less than SOC loss. In addition, under CK, SOC is depleted due to nutrient withdrawal during continuous cropping (Manna et al., 2007). In contrast, manure applications combined with inorganic fertilizers can lead to SOC increase by 30% to 40% while still stimulating crop yields (Jiang et al., 2017).

N and P are the major limiting nutrients in crop production. The yield under NPK is comparable to that from NPKM because nutrients are readily released from mineral fertilizer to stimulate crop growth. Without P application, the yield of some sites (e.g. YL and ZZ) decreased rapidly while yields remained relatively stable in some other sites (GZL, Urum, and HZ), which is probably related to P limitation (Syers et al., 2008). For the CK treatment, there is no fertilizer input and nutrients supply depends solely on basic soil fertility. Although manure addition and chemical fertilizers can lead to an increase of crop yield and SOC stock in the soil, the application rate and management of organic and chemical fertilizer still need to be optimized to reduce environmental cost, especially for the manure management in China (Ju et al., 2009).

4.2. Performance of the EPIC model

The EPIC model can accurately simulate crop yield and soil C dynamics in cropland of China. Wang et al. (2010) applied the EPIC model to

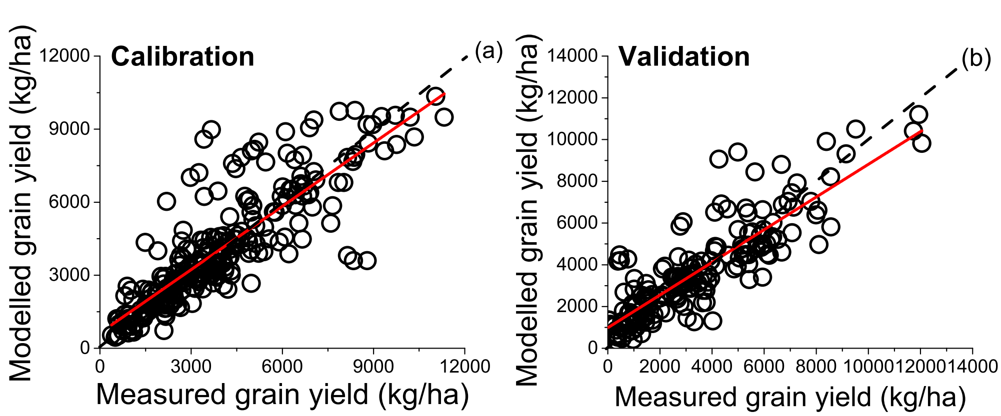

Fig. 6. Observed and simulated crop yield for the 8 experimental sites and all treatments (a) results of the calibration period (1990–1996) and (b) validation period (1997–2000).

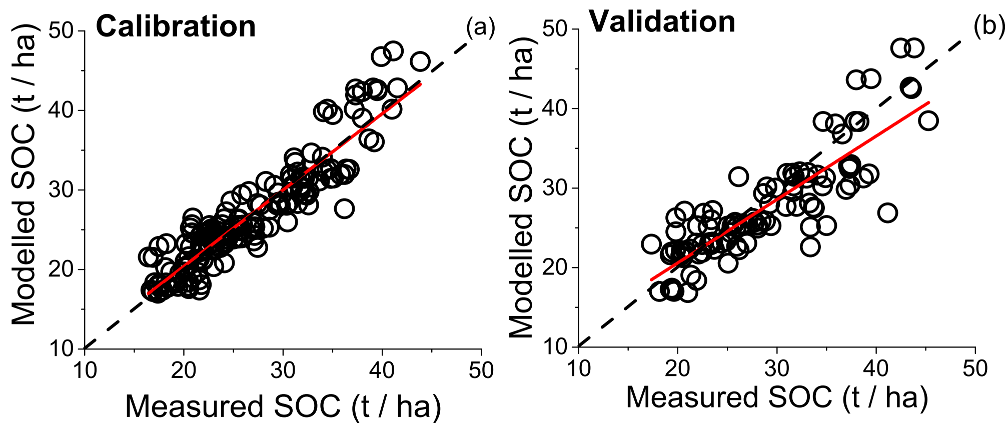

Fig. 7. Observed and simulated SOC for the 8 experimental sites and all treatments. (a) results of the calibration period (1990–1996) and (b) validation period (1997–2000).

study the upland soils in the Loess Plateau of China and reported that the crop yield simulation agreed well with the measured experimental data. Liu et al. (2007) used the EPIC model to study the irrigation effect on winter wheat yield and crop water productivity in China. EPIC was also used to explain historical changes in soil organic carbon stocks in the Roige wetland of China by Ma et al. (2016).

The complex crop management in China imposes additional requirements for EPIC. There are several reasons for disagreement between model and observations. Firstly, the simulated SOC represents the modeled SOC content at the end of the year, while observations refer to a specific sampling date. Secondly, rice transplanting is a common practice in China. However, the EPIC model does not include this practice and it simulates crop growth from sowing, which leads to a delayed biomass accumulation by one to two months compared to transplanting, leading to underestimation of rice yields by EPIC. Thirdly, soil acidification is one of the most important factors limiting nutrient uptake and crop yields (Zhang et al., 2008). For site Qiyang (QY), the pH of the local red soil has significantly decreased after long-term fertilization. In 1990, the pH was 5.7 while a significant decrease of pH can be detected among treatments with inorganic fertilizer after three years. After long-term fertilization, in 2000, the pH of NPK, CK, and NK were only 4.7, 5.6 and 4.7 (Cai et al., 2011;Qu et al., 2014). Soil pH would completely inhibit wheat and corn growth if the value declined to less than pH 4.2 (Zhang et al., 2008). Currently, the significant crop yield reduction caused by soil acidification within the observed range of pH is not adequately modeled by EPIC, which explains why modeled yields exceed observations (site QY, see Fig. 3). Further model development remains desirable to incorporate the complex effects of pH on crop yield and soil nutrient availability.

Other discrepancies between observations and model simulation may be related to the impact of crop diseases, insect outbreaks and hail, which are not considered and modeled by the EPIC model. Currently, only water, soil nutrients, temperature, soil aeration, salinity and aluminum stresses are included.

4.3. The relationship between crop yield and SOC

Crop yields show a good correlation with SOC, especially under the CK treatment. In this case, the crop yield mainly depends on soil fertility to supply the required mineral nutrients (Zhang et al., 2016a;Yan and Wei, 2010). However, crop yields show larger variation than SOC, mainly arising from seasonal variation and agronomic practices. SOC varies mainly by simultaneously changing the balance between organic matter addition and SOC decomposition (Li et al., 2003;Wang et al., 2010). Both processes are regulated by the primary drivers, i.e., climate, soil properties, crop type, and farming practices, including tillage and crop rotation systems and inputs from crop residue incorporation and manure application (Hernanz et al., 2002; West and Post, 2002;Fei et al., 2009).

5. Conclusion

This study analyzes the effects of diverse fertilization practices on crop yield and SOC in China based on long-term field experiments,

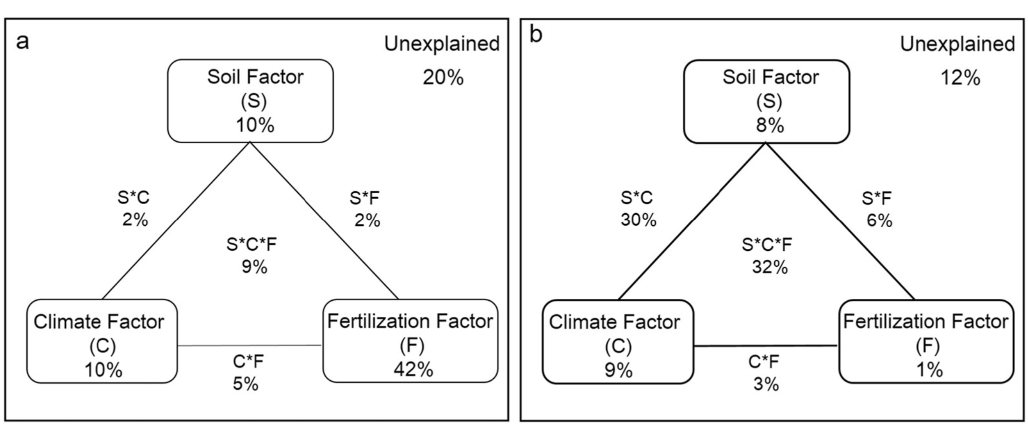

Fig. 8. The contribution (%) of the independent factors soil, climate, and fertilization and their interaction on the variability of (a) crop yield and (b) SOC at the eight long-term field experiments in China, based on the variance partitioning analysis (VPA) conducted among four fertilization treatments (NPK, NK, CK and NPKM) from 1990 to 2000. S*F indicates the interactive contribution of soil factor (S) and climate factor (C) and S*C*F mean the overall interactive contribution of the three factors.

modelling with the EPIC model, and VPA analysis. The highest and lowest (30%–50% of NPK yield) crop yield and SOC content were found under the NPKM and CK treatment, respectively. The SOC showed a large spatial variability across eight experimental sites in China and that in Northern sites appeared more dynamic than in southern sites. SOC content increased at Gongzhuling (GZL), Changping (CP), Yangling (YL), and Beibei (BB) under all fertilization treatments while it decreased at Urumqi (Urum) under NPK, CK and NK treatments. The fertilization factor explains most of the crop yield variability (42%) while the SOC variance was largely determined by the interaction of soil and climate factors (32%).

EPIC simulations adequately describe crop yields and SOC dynamics under a range of long-term fertilizer management across different regions, cropping systems and weather conditions of China. Improving EPIC model to accurately simulate rice-transplanting and soil acidification would lead to a closer agreement between model and observed changes.

A close coupling of long-term field experiments with bio-physical process modelling is a useful approach to summarize experimental data, improve our understanding of the influence of fertilization on soil properties such as SOC and crop production, optimize fertilizer application rates and maintain soil fertility, and extrapolate the results to regions where experimental farms are lacking.

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